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A Regression Model for the Western North Pacific Tropical Cyclone Intensity Forecast

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Tropical cyclone forecasting is an important but difficult task. The term "intensity" refers to the maximum surface or low-level wind speed associated with a tropical cyclone. A regression model for forecasting this wind intensity in the western North Pacific was derived by using the 19-year (1971-89) post-determined best-track data, which include the date, time and location of the tropical cyclone's circulation (cyclonic) center, and the estimated maximum sustained surface wind speed (one-minute average at 10-meter elevation). This model provides intensity forecasts out to 72 hours for 12-hour intervals, and is designed for the intensity of all classes of tropical cyclones in the western North Pacific. To establish characteristics of this regression model, intensity forecasts from the model are compared with official forecasts from the Joint Typhoon Warning Center at Guam and with forecasts from a persistence method, for the year 1990, in terms of relative statistics.

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CONTENTS

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A REGRESSION MODEL FOR THE WESTERN NORTH PACIFIC TROPICAL CYCLONE INTENSITY FORECAST

1. Introduction

The maximum surface sustained wind speed, the "intensity", associated with a moving tropical cyclone can cause devastating wind pressure forces, severe storm surges, and swells in an area much broader than the area of the storm itself. Thus, intensity becomes a measure of a tropical cyclone's violence. Intensity forecasts have long been issued for the Atlantic and Pacific ocean regions; nevertheless, predicting tropical cyclone intensity accurately continues to be one of the major problems confronting forecasters. This difficulty is due mainly to the fact that both the spatial confinement of an axially asymmetric strong wind zone and the characteristics of the moving nature of a tropical cyclone are too complicated to be observed adequately and economically. Furthermore, the necessary and sufficient conditions that cause the intensity and its local change are not well understood. Strong winds are usually found in a narrow circle surrounding the warm core of a mature tropical cyclone. In addition, the vertical structure of strong wind and vertical motion can have noticeable variations in both time and space. The routine synoptic data in the vicinity of a tropical cyclone generally are too sparse to quantify the physical interactions among all energy-bearing scales of motions for all stages of intensity development.

With satellite cloud imagery analysis, the cyclone intensity can be inferred from the cloud patterns (Fritz *et al.*, 1966; Dvorak, 1975). The accuracy of this intensity estimation method can reach 60% of total cases with 15 kt class intervals (Hubert and Timchalk, 1969). The Joint Typhoon Warning Center (JTWC), Guam, has developed an experimental Northern Hemisphere Intensity Forecast Checklist by extending the Dvorak Scheme (Dvorak, 1975) with the upper tropospheric flow pattern and the sea surface temperature. This checklist provides indices that are related to 24-, 48- and 72-hour intensity forecasts.

Numerical simulations of tropical cyclones are logic tools for verifying the necessary conditions for intensity change. Using a balance model with nearly infinite speeds of gravity waves, Ooyama (1969) successfully simulated the life cycle of an average tropical cyclone (Ramage, 1970); nevertheless, the development of prognostic models together with initialization procedures is still an ongoing research topic. Meanwhile, the junior forecasters have to rely upon senior forecasters' experience (scientific, non-scientific, and politic), thumb rules, decision-tree methods, or regression models to forecast tropical cyclone intensity (Elsberry *et al.*, 1992).

Regression models for cyclone intensity forecasts are popular at operation centers, because they provide quick and reliable guidance to the duty forecasters. The skill of such models comes from the selection of predictors. The selection is usually guided by experience, conceptual models, availability of data type, methods of data stratification, and data quantity and quality. The selection procedure can be subjective and empirical; therefore, one effective way to test and improve an empirical model is by verifying the model forecast and adjusting the selections accordingly. Thus, a close tie between an empirical model and its forecast verification is intrinsic. Elsberry *et al.* (1975) used 10-year data (1960-69) in the western North Pacific and derived a regression and synoptic model for predicting cyclone intensity from cyclone location, past motion, intensity, intensity change, and the latitude of the 700 mb ridge. Jarvinen and Neumann (1979) used 92 years of data (1886-1977) to obtain regression models for intensity predictions in the Atlantic. They also concluded that using persistence for intensity forecasting is valid for a 12 hr forecast, but deteriorates for a 72 hr forecast. Their Statistical Hurricane Intensity Forecast model (SHIFOR) has been adopted by the National Hurricane Center as a tropical cyclone intensity forecast aid.

As requested, NRL Monterey has adapted SHIFOR for western North Pacific topical cyclones. The main purpose of this paper is to discuss the results of the Statistical Typhoon Intensity Forecast (STIFOR) model which is designed for use at JTWC as a tropical cyclone forecasting aid. Intensity forecasts obtained from STIFOR are compared with the official forecasts from the JTWC, and with the forecasts from a persistence method, for the year 1990, in terms of their statistics.

2. Data and Methods

The 20-year (1971-90) JTWC post-determined western North Pacific best-track data are used in this study. The best-track data consist of a tropical cyclone's identification, date and time, center location, and intensity, where intensity is the maximum sustained surface wind speed (1-min average at 10-m elevation). The intensity data before August 1987 were mainly obtained from the automatic navigation systems aboard reconnaissance aircraft, and the data after that time were obtained from human analysts. The intensities vary from 20 to 180 kt. A tropical cyclone's motion and its intensity changes were computed by using the post-determined best-track data. The working database contains seven parameters: tropical cyclone date (JD_0), current location in latitude and longitude in degrees (La_0 and Lo_0), the past 12-hr zonal and meridional components of tropical cyclone motion in kt (CU_{-12} and CV_{-12}), the intensity in kt (I_0), and the past 12-hour intensity difference in kt (DI_{-12}).

Regression models for forecasting are usually built by mapping the predictors onto predictands with a predetermined base function. The linear function for this study is

$$I_{hh} = (C_1, C_2, C_3, C_4, C_5, C_6, C_7, C_8)\,(JD_0, La_0, Lo_0, CU_{-12}, CV_{-12}, I_0, DI_{-12}, 1)^T, \qquad (1)$$

where the predictand I_{hh} denotes the intensity at hh hours which is 12, 24, 36, 48, 60 or 72 hr; and the C_n, n=1, ...8, denote the eight constant coefficients that are usually determined from the data by using a regression method. The superscript T indicates the transpose of the predictor matrix. C_8 is the bias of regression. The physical dimensions of these coefficients are implicit.

The future intensities I_{hh} on the left side of Eq. (1), are expressed as a linear combination of observable predictors on the right side of it. The linear dependencies are assumptions which need verification. Figures 1 to 7 are the 19-year (1971-89) histograms representing the joint distributions between the intensity, I_{hh}, and one of the right-hand-side variables of Eq. (1). Parts (a) and (b) of each figure are the 12-hour and 72-hour intensities, respectively. Similar figures for the 24-, 36-, 48-, and 60-hours are not shown. The data number decreases with increasing hours. For example, the data number for 12-hr intensity is 14,975, but that for 72-hr is only 9,543. There are several features shown in these figures:

(1) For 12-hour (short-period) persistence, the best linear dependence is between I_{12} and I_0 (Fig. 6a). This indicates that persistence can be a good short-term forecast method. The second best is between I_{12} and DI_{-12}. Figure 7a shows that the past 12-hr tendency of intensity can provide useful information to the short-term intensity forecast.

(2) For 72-hour (long-period) persistence, the linear dependence between I_{12} and I_0 (Fig. 6b) is less clear than that between I_{12} and I_0 (Fig. 6a). Similar characteristics are true for other parameters. For example, the past 12-hr tropical cyclone motion provides insignificant information to the 72-hr intensity forecast (Figs. 5b and 6b). Therefore, the average performance of this regression model for a 72-hr intensity forecast is expected to be poorer than that for a 12-hr forecast.

(3) Information content among predictors varies. Figures 2a, 3a, 4a and 5a show that the relations between intensities and other predictors are not linear. This nonlinear character can not be properly represented by the linear regression model, Eq. (1). For example, the latitude and longitude provide little useful information to the 12-hr intensity forecast (Figs. 2a and 3a). Using eight-year (1950-57) tropical cyclone minimum surface pressure in the western North Pacific, Frank and Jordan (1960) showed that the intensities of tropical cyclones exhibit somewhat latitudinal but not longitudinal variations. The patterns in Figs. 2a and 3a indirectly support their findings.

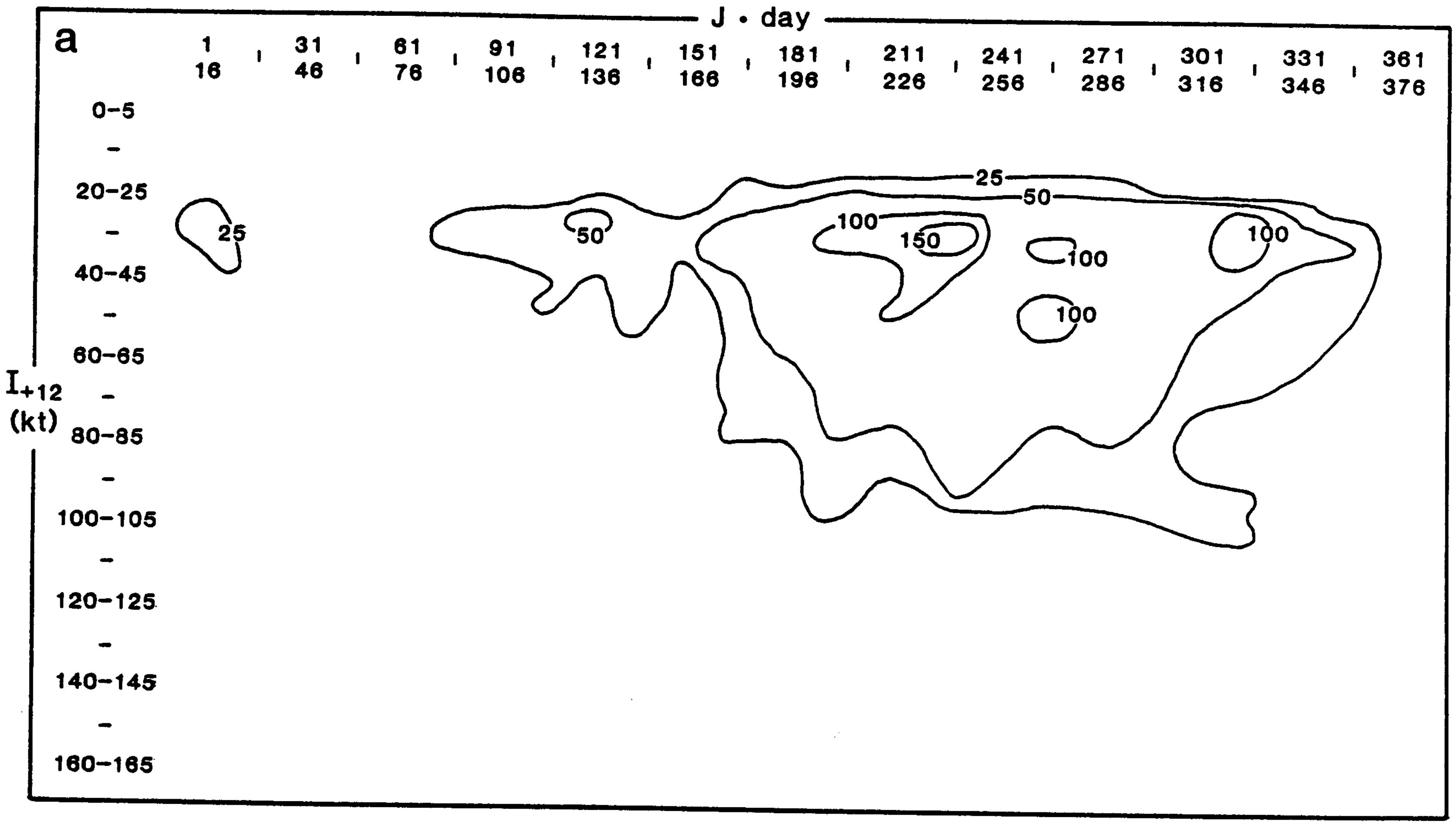
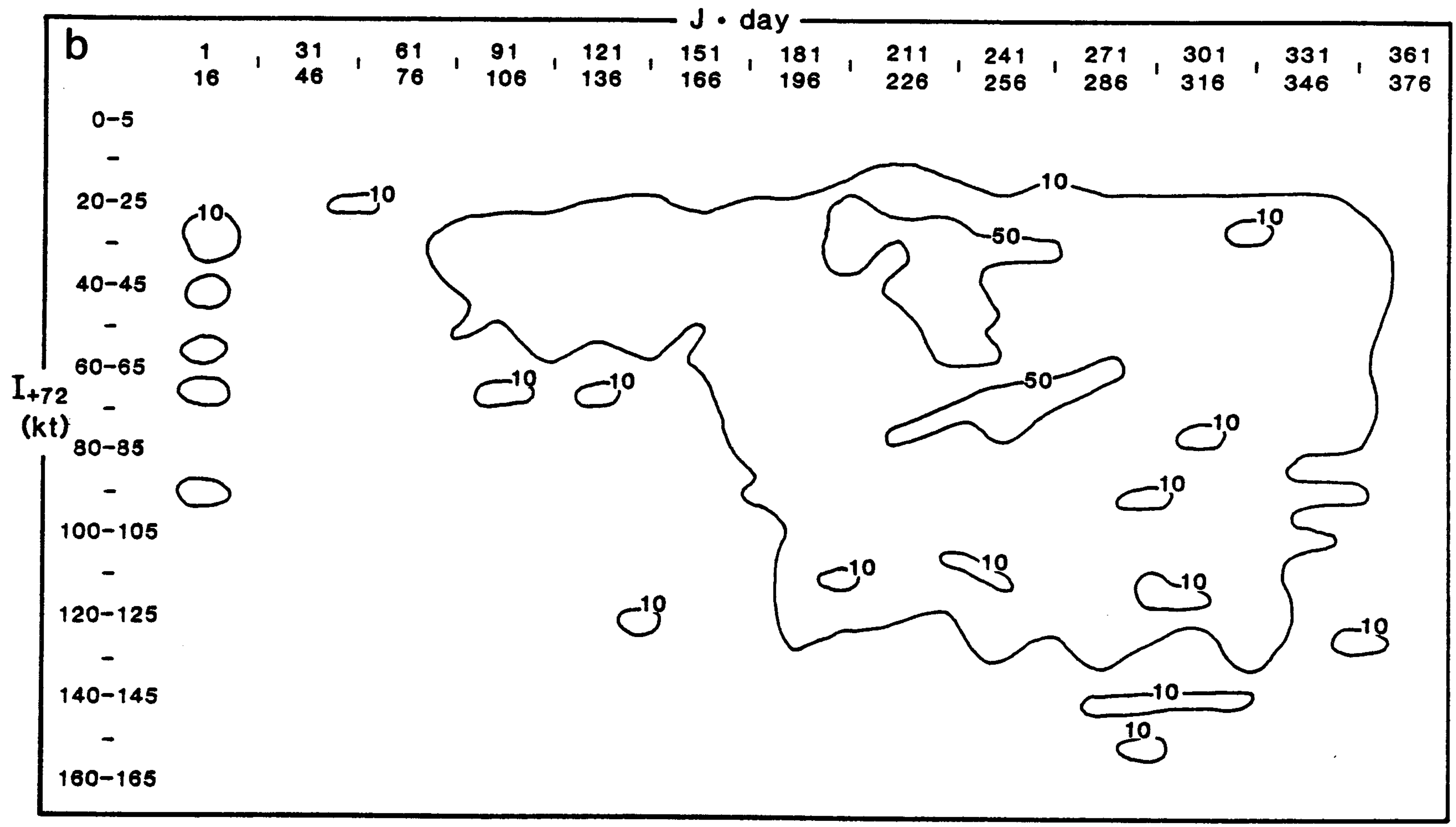


Figure 1. A 19-year (1971-89) histogram representing the joint distribution between the tropical cyclone intensity (in kt) and Julian day (Jday). Parts a and b are the distribution for 12-hr and 72-hr intensities (), respectively.



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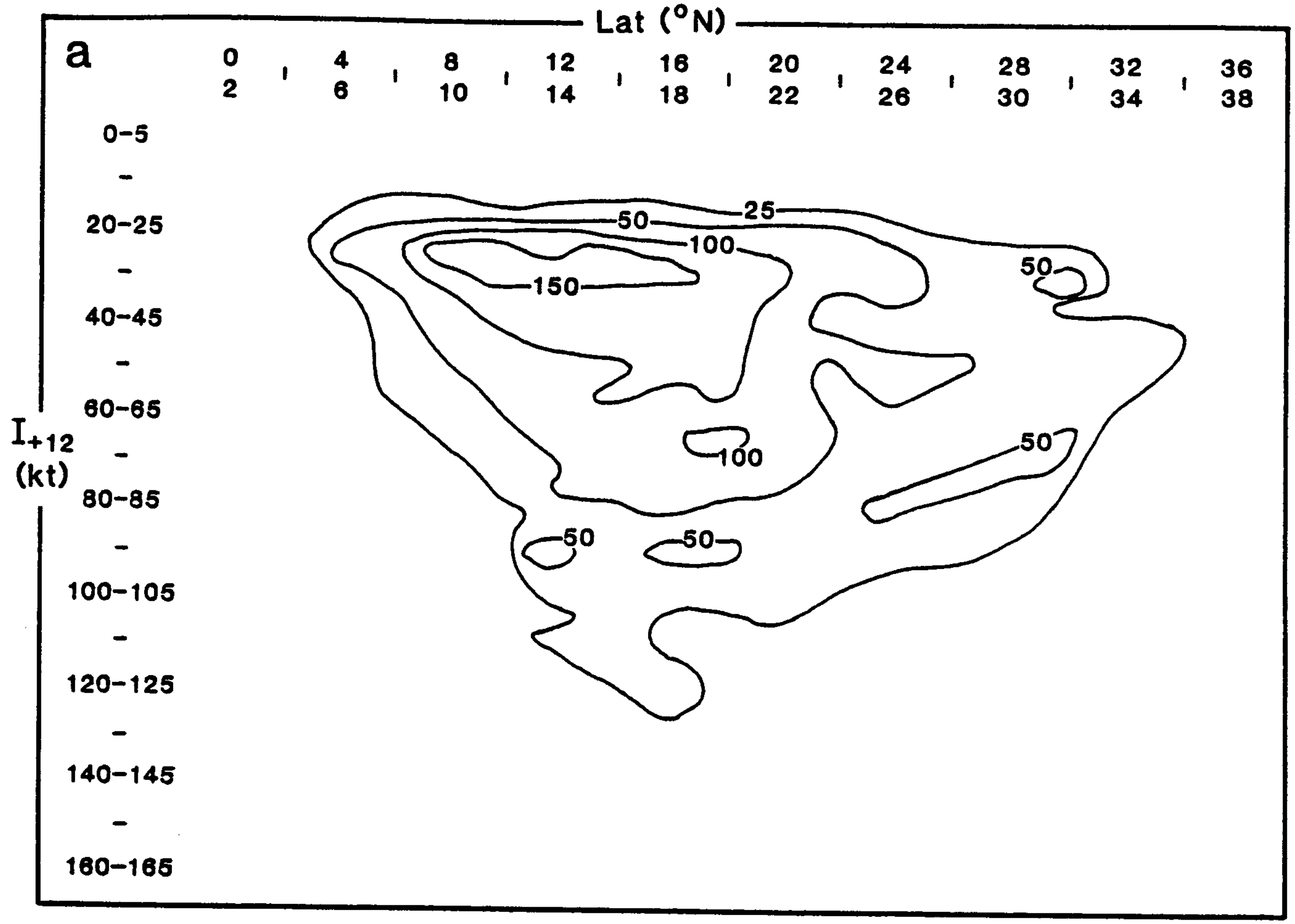
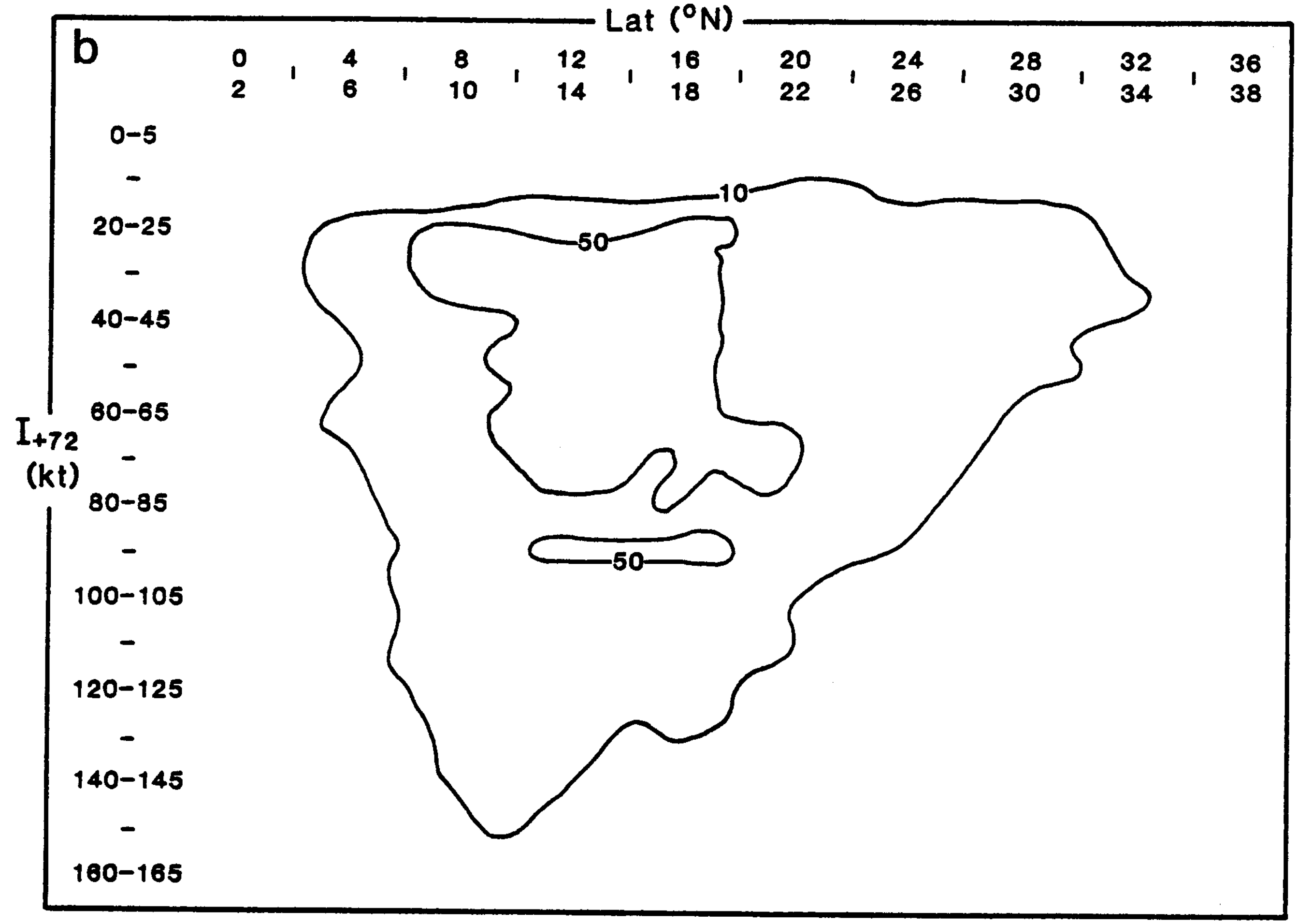


Figure 2. Same as Fig. 1, except for intensity and latitude of tropical cyclone location (La_0).



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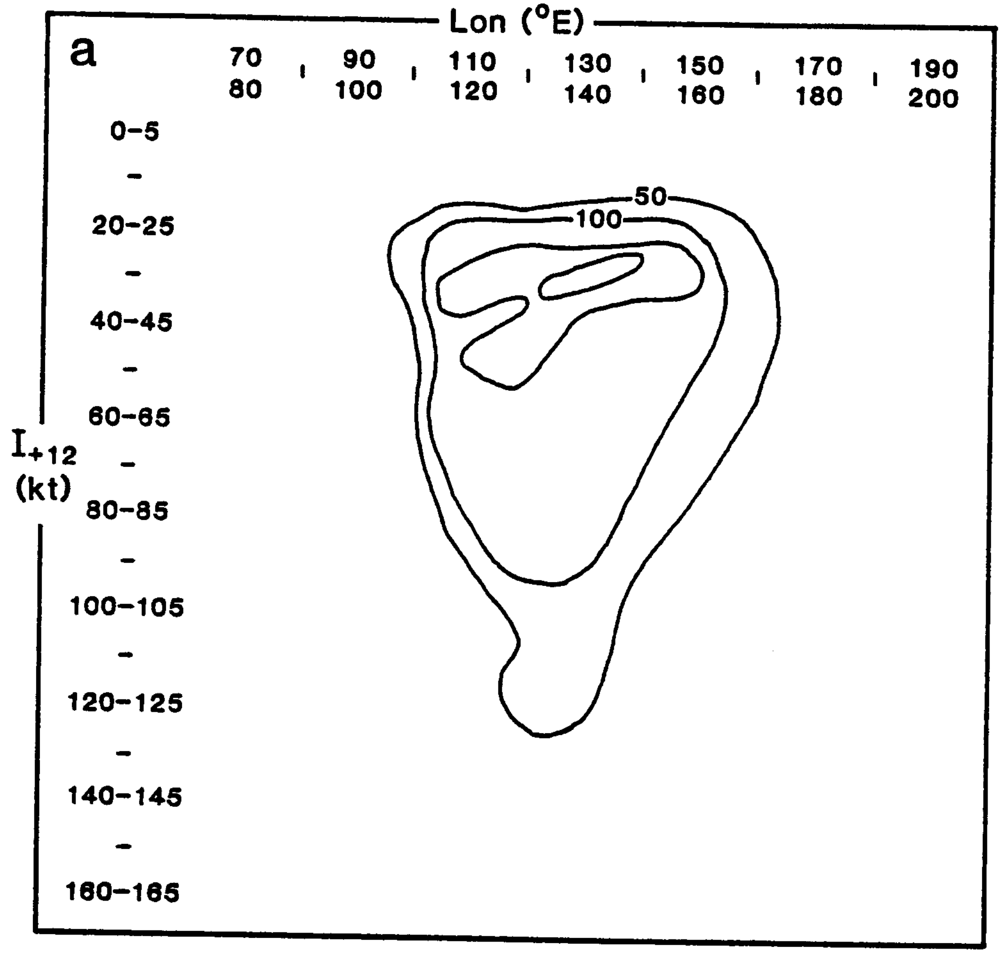
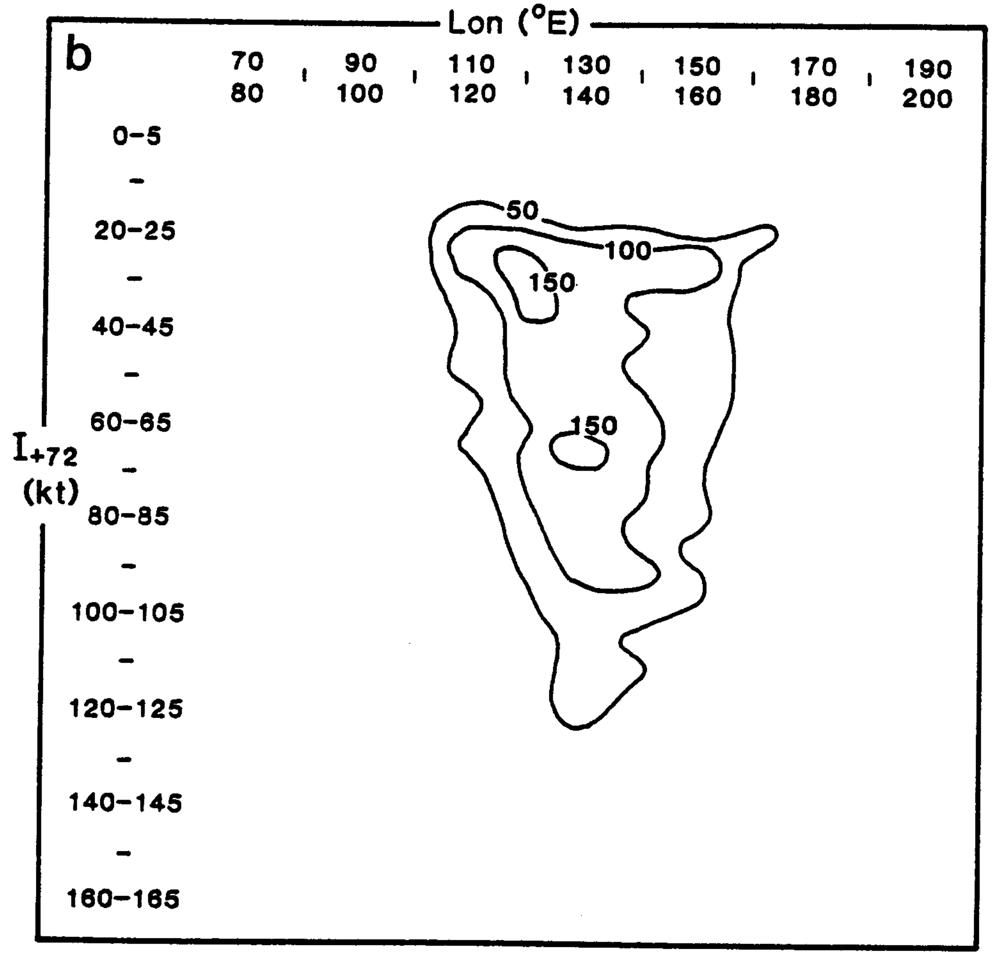


Figure 3. Same as Fig. 1, except for intensity and longitude of tropical cyclone location (Lo_0).



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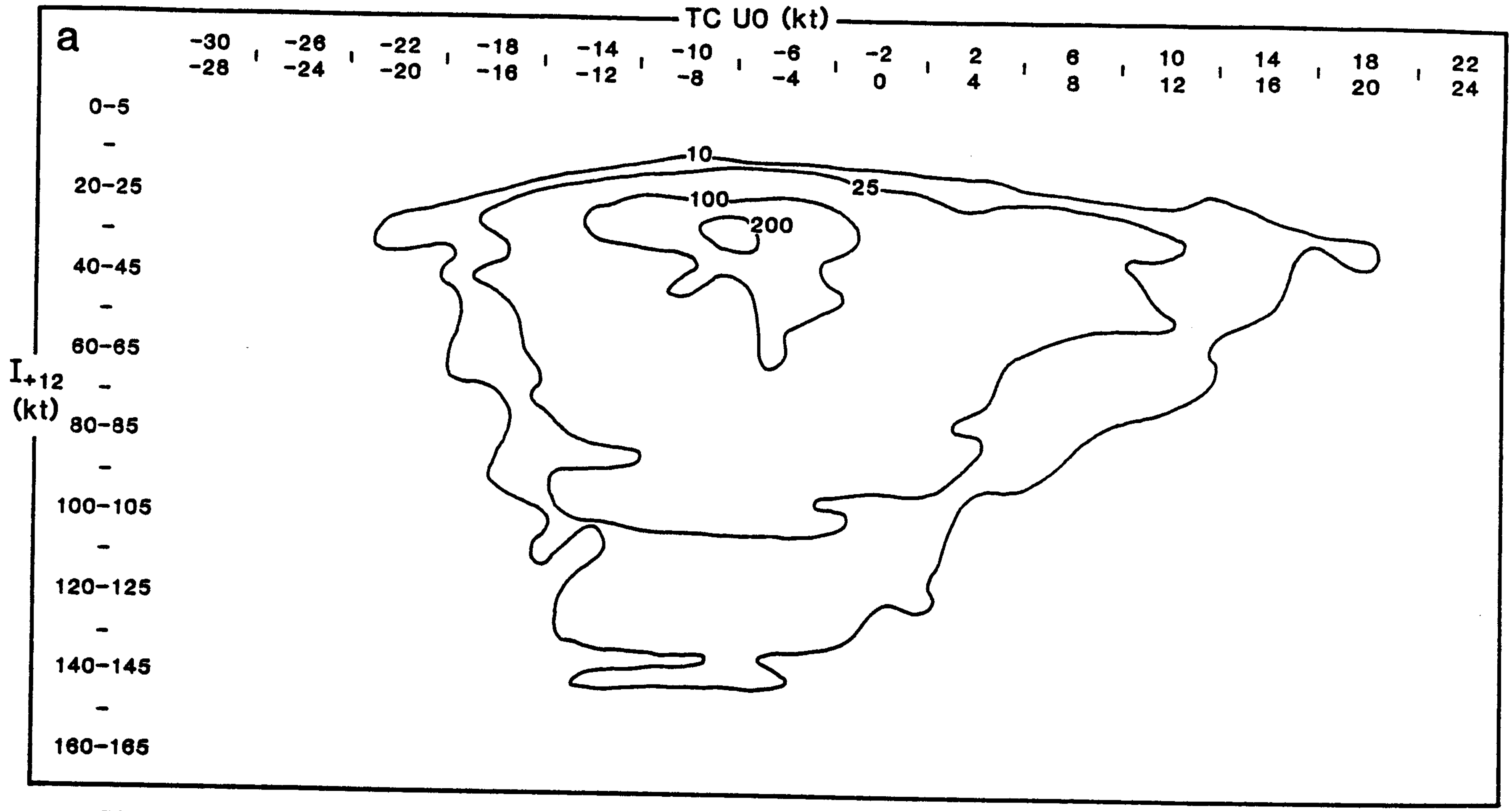

Figure 4. Same as Fig. 1, except for intensity and the past 12-hr zonal component of tropical cyclone motion in kt (CU_{-12}).

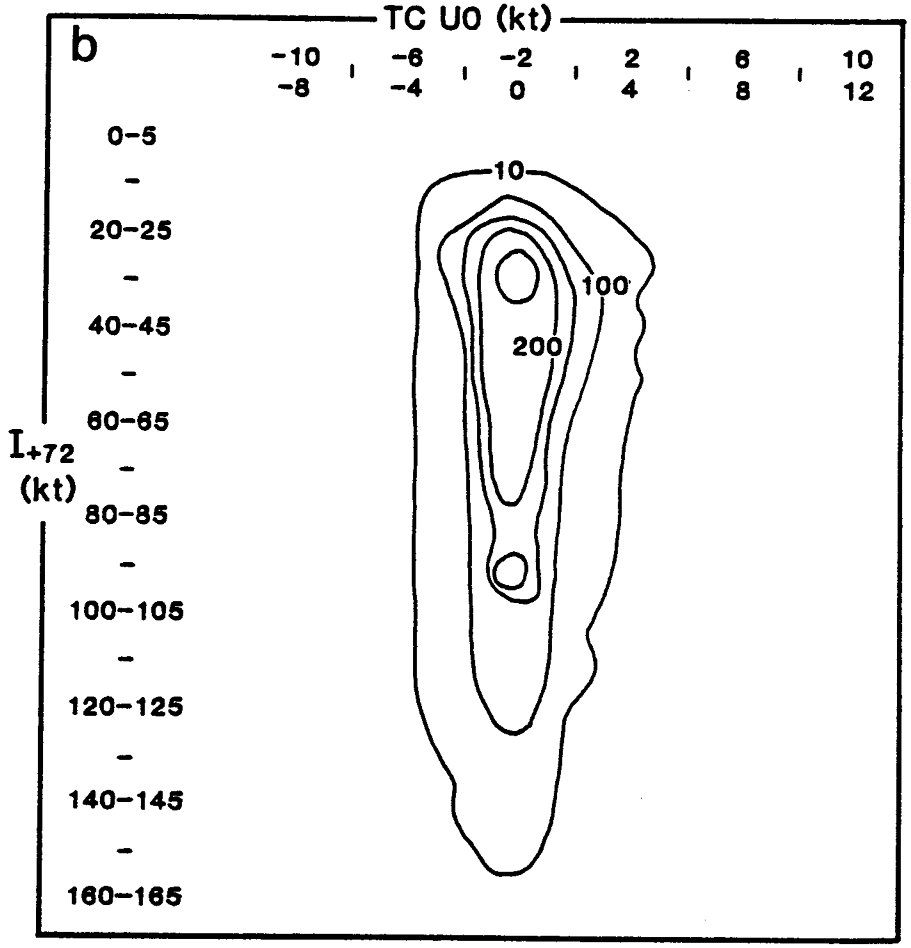

Figure 4 , continued.

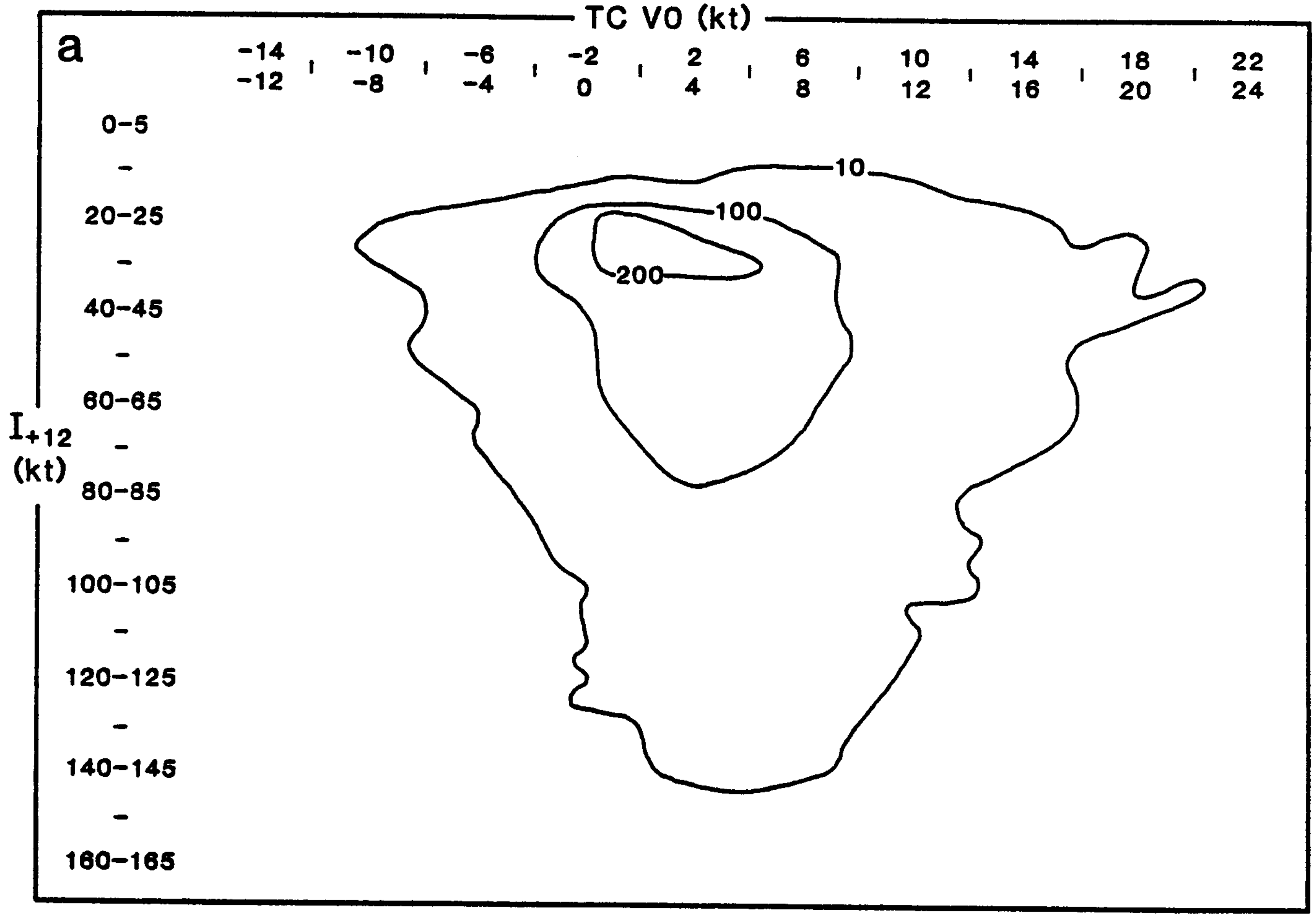

Figure 5. Same as Fig. 1, except for intensity and the past 12-hr meridional component of cyclone motion (CV_{-12}).

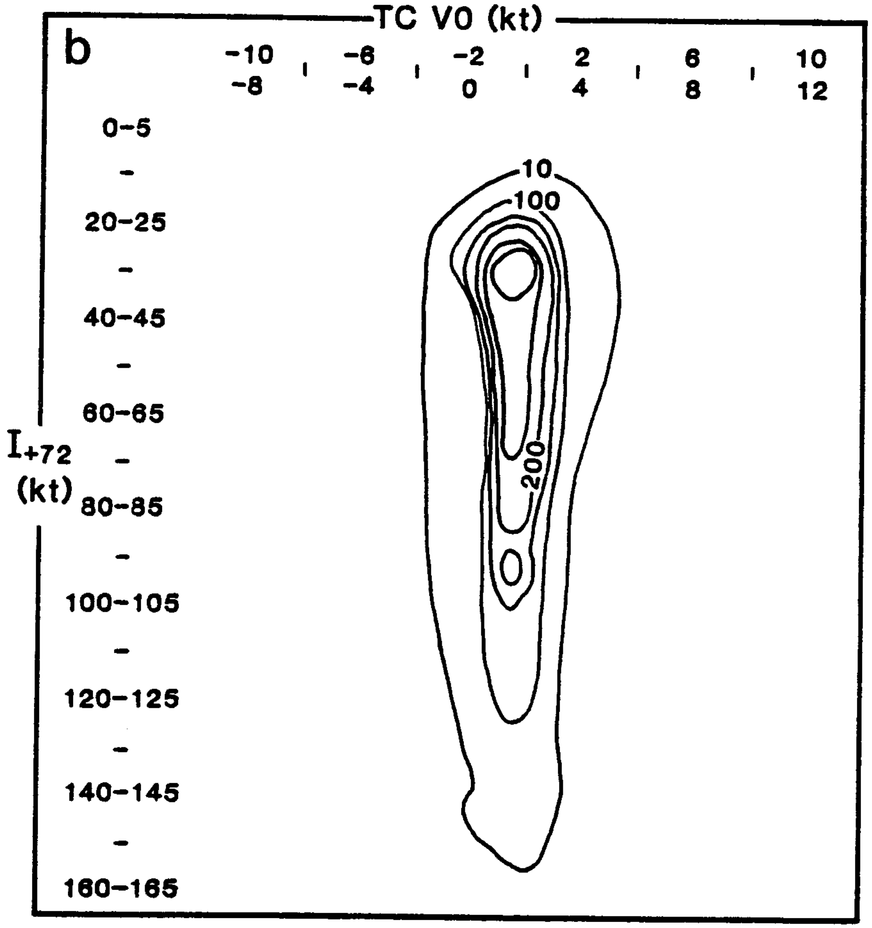

Figure 5, continued.

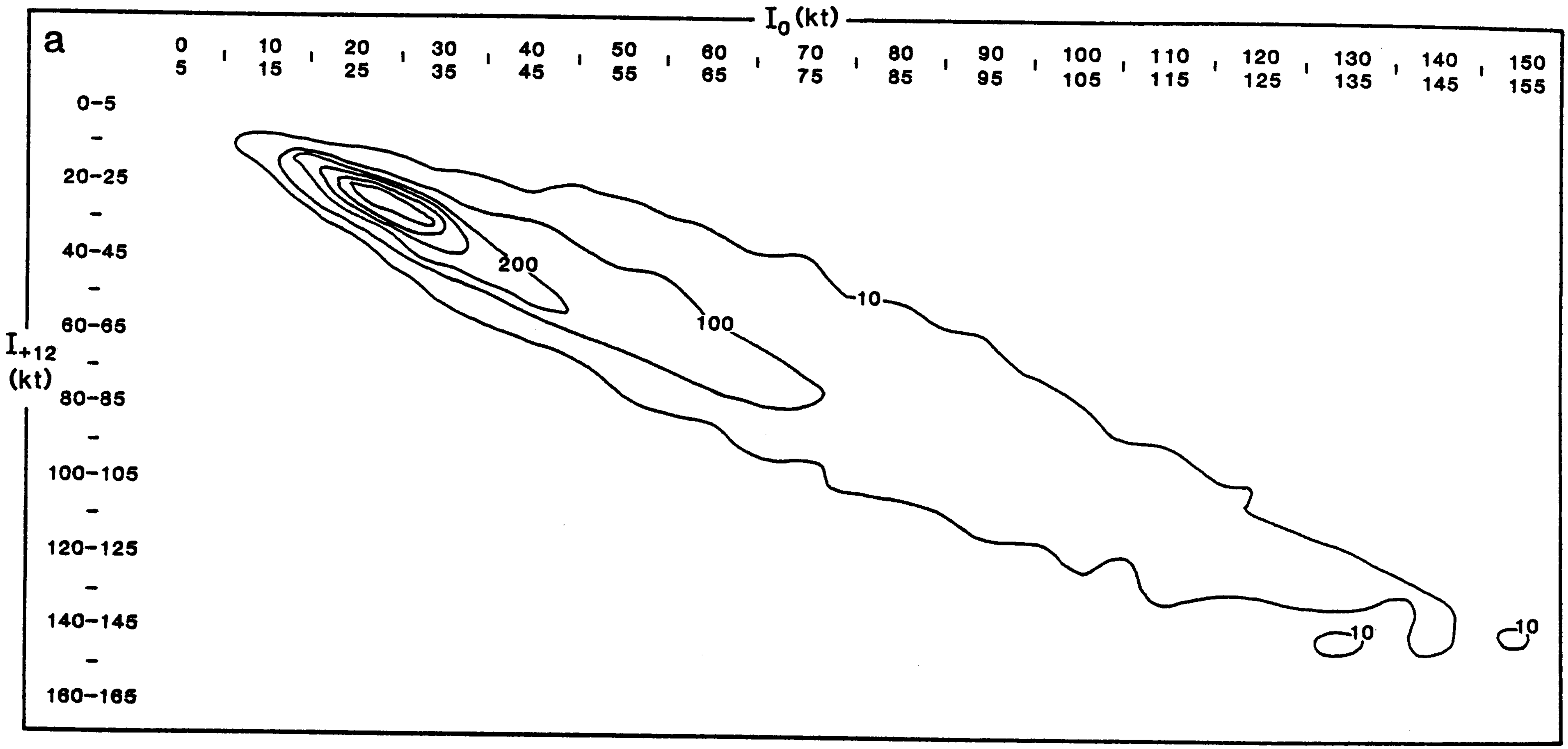

Figure 6. Same as Fig. 1, except for intensity and tropical cyclone intensity (I_0).

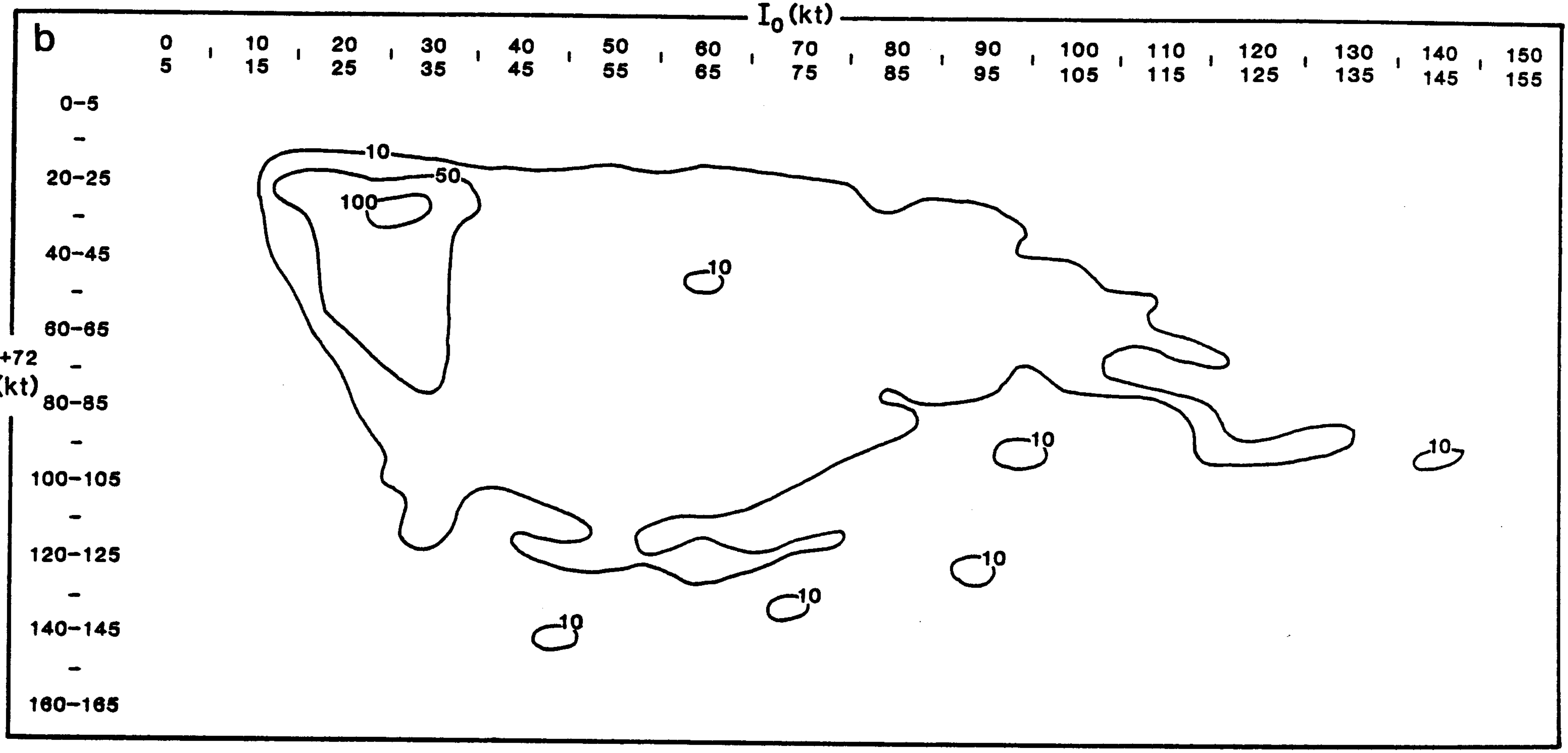

Figure 6, continued.

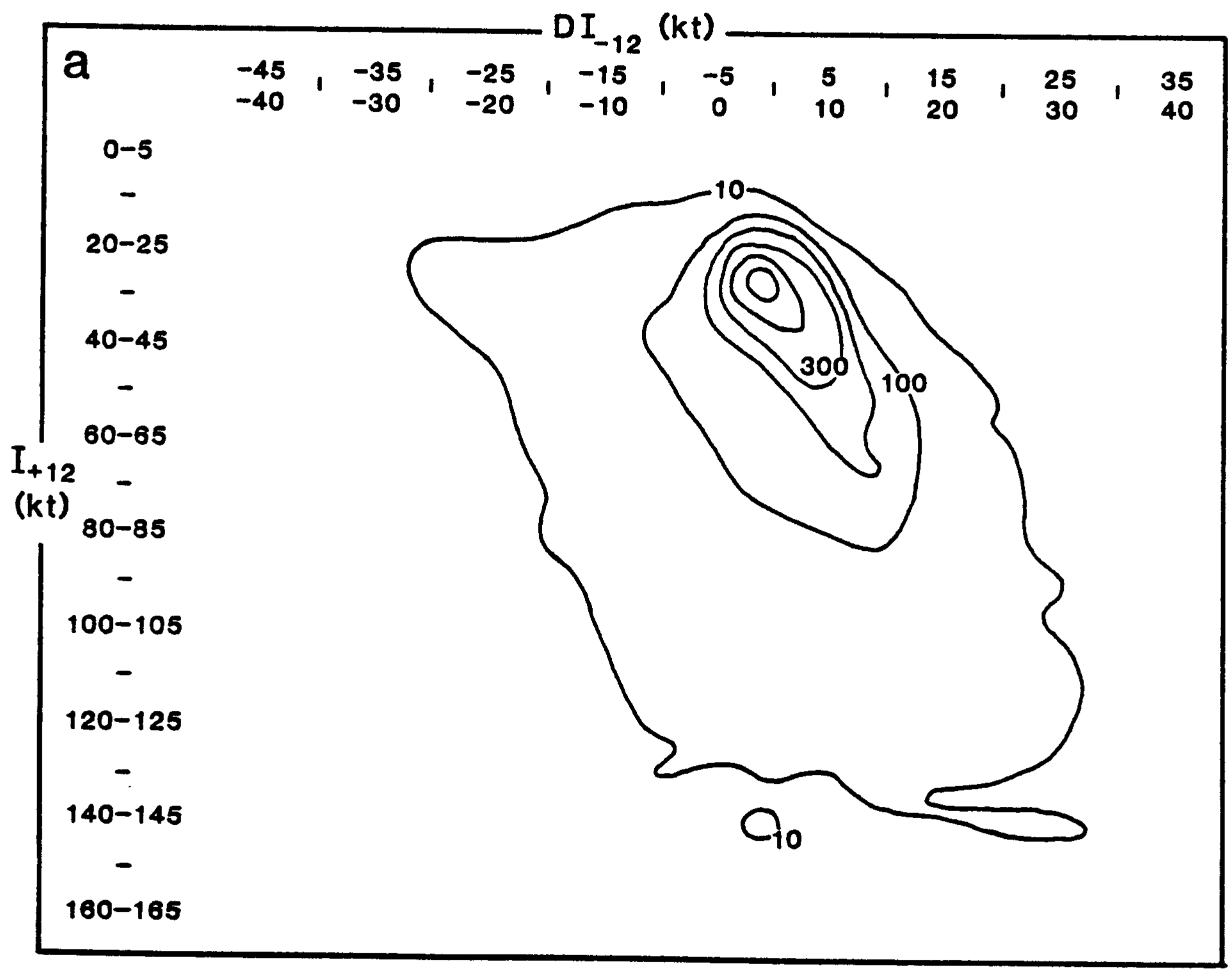

Figure 7. Same as Fig. 1, except for intensity and the past 12-hr change of tropical cyclone intensity (DI_{-12}).

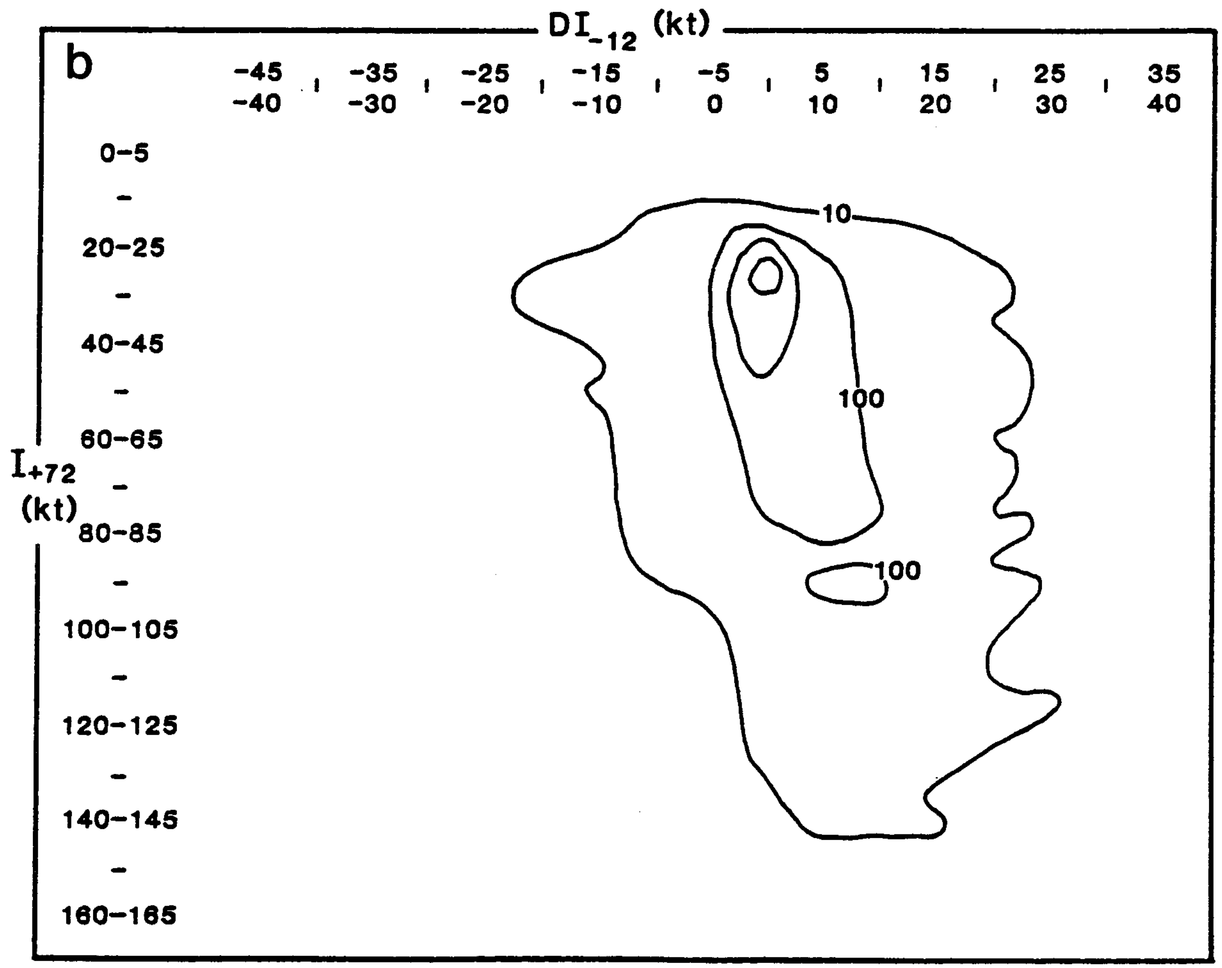

Figure 7, continued.

3. Results

The coefficients C_n in Eq. (1) have been obtained through the least-squares method by using a set of 19-year (1971-89) JTWC tropical cyclone data. These coefficients represent linear relationships between the predictand and predictors in Eq. (1). Table 1 is the list of the values of these coefficients for the 12-, 24-, 36-, 48-, 60-, and 72-hr formula, respectively. These coefficients are used in the STIFOR model. It is worth noting that the coefficients obtained from other periods of the JTWC data, such as 1971-82, 1971-83, etc., are similar to those in Table 1. This suggests that the STIFOR model does not require an annual update, unless a drastic change in intensity characteristics takes place.

Table 1. The coefficients (Coef.) and corresponding parameters (Para.) in Eq. (1) for 12-, 24-, 36-, 48-, 60-, and 72-hr intensities. The data source is the JTWC post-determined best-track data during the period 1971-89.

Coef.	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	Para.
C_1	0.004	0.011	0.019	0.026	0.033	0.039	JD_0
C_2	-0.148	-0.346	-0.532	-0.696	-0.811	-0.903	La_0
C_3	0.077	0.165	0.244	0.315	0.378	0.430	Lo_0
C_4	-0.053	-0.213	-0.363	-0.547	-0.625	-0.717	CU_{-12}
C_5	-0.019	-0.074	-0.237	-0.667	-1.390	-2.550	CV_{-12}
C_6	0.908	0.775	0.633	0.498	0.374	0.260	I_0
C_7	0.496	0.715	0.796	0.797	0.781	0.740	DI_{-12}
C_8	-4.09	-6.93	-7.87	-8.25	-8.92	-9.56	1

It is worthwhile to note that tropical cyclone intensity is a positive quantity. This condition may be violated when Eq. (1) is used, together with the coefficients in Table 1, to prepare an intensity forecast. The lower and upper bounds for intensity obtained from Eq. (1) are set at 0 and 200 kt, respectively. Although predicted intensities below 15 and above 160 kt are beyond the limits of the historical data, and intensity below 20 kt is meaningless; these predictions could provide useful intensity trend guidance.

The STIFOR model was used for making 1990 tropical cyclone intensity forecasts. The results from STIFOR were then compared with JTWC official forecasts and forecasts from a persistence method which predicts that the future intensity will be the same as the present one. Table 2 summarizes the comparisons among the three methods in terms of statistics. The statistics consist of five parts: root-mean-square error, mean and standard deviation of absolute error, coefficient of linear correlation, covariance, and accuracy for a 10-kt interval. From Table 2, we observe the following:

(1) In terms of root-mean-square error, absolute errors, and linear correlation, STIFOR is the best model for forecasting intensity up to 48 hr.

(2) The absolute errors indicate the performance of all three forecasts beyond 48 hr is poor.

(3) The results from the persistence method have the fastest decrease of correlation up to 48 hr.

(4) Covariance is a measure of the variations of magnitude of two series of data. The covariance between the intensities from the persistence method and the best-track intensity are greater than the covariances from the other two methods versus the best-track intensity.

(5) In terms of the accuracy in a 10-kt interval, STIFOR provides the most skill for 12-hr intensity forecasts. The three methods have comparable skill for the 24-hr forecasts. JTWC's skill is the best for the 48- and 72-hr forecasts. The accuracy is defined as the ratio between the number of correct forecasts and the total forecasts, and is expressed in percent.

The accuracy can also be displayed in matrix format, in order to see the scattering pattern around the correct forecast. Figure 8 (8a, 8b and 8c) shows the accuracy matrices for the 12-hr intensity forecasts from the three forecast methods: STIFOR, JTWC, and persistence. Their scattering patterns are similar. Figure 9 is the same as Fig. 8, but it is for the 72-hr intensity forecasts. The forecast from JTWC (Fig. 9b) has less scattering than that from the other two methods. The STIFOR forecasts the cyclone intensities of a narrow range (40-70 kt) into a wide range (10-100 kt). On the other hand, the persistence forecasts fail to distinguish the best-track intensities between 20 and 100 kt. The overall scattering patterns of the 72-hr forecasts by using all three methods are much greater than those of the 12-hr ones. This indicates the severe limitation of a 3-day intensity forecast by the current regression method. The scattering patterns of the 24- and 48-hr forecasts are not shown; however, they lie in between the corresponding patterns in Figs. 8 and 9.

Table 2. Verifications of 1990 results from STIFOR, JTWC and the persistence method (PERSIST.) with the post-determined best-track intensity for the western North Pacific. The statistics consist of five parts: root-mean-square error (RMSE), mean and standard deviation of absolute error (AE), coefficient of linear correlation, covariance (COV), and accuracy for a 10-kt interval (ACCU). The numbers of available data are in the parentheses of the RMSE part. The values in the parentheses of the AE part are the standard deviations of AE.

		12 hr	24 hr	48 hr	72 hr
1. RMSE (kt)					
	STIFOR	6 (1182)	12(1120)	23 (996)	32(875)
	JTWC	12 (669)	15 (592)	23 (390)	31(227)
	PERSIST.	9 (1182)	17(1120)	30 (996)	39(875)
2. AE (kt)					
	STIFOR	5 (5)	10 (8)	18 (13)	23 (16)
	JTWC	10 (8)	13 (10)	19 (15)	24 (22)
	PERSIST.	10 (6)	16 (11)	25 (19)	33 (24)
3. Correlation					
	STIFOR	0.98	0.94	0.81	0.53
	JTWC	0.92	0.86	0.66	0.35
	PERSIST.	0.96	0.86	0.59	0.34
4. COV (10^2 kt^2)					
	STIFOR	9	8	5	3
	JTWC	8	7	5	2
	PERSIST.	10	9	6	4
5. ACCU (%)					
	STIFOR	55	30	14	11
	JTWC	42	30	23	18
	PERSIST.	49	30	17	14

STIFOR Intensity Forecast (kt)

a

Best-Track Intensity (kt)	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-H0	H0-H1	H1-H2	H2-H3	H3-H4	H4-H5	H5-H6
0- 10	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10- 20	0	**39**	19	0	0	0	0	0	0	0	0	0	0	0	0	0
20- 30	0	29	**248**	50	4	0	0	0	0	0	0	0	0	0	0	0
30- 40	0	0	34	**132**	45	7	0	1	0	0	0	0	0	0	0	0
40- 50	0	0	4	20	**51**	32	2	0	0	0	0	0	0	0	0	0
50- 60	0	0	0	2	14	**33**	32	3	0	1	0	0	0	0	0	0
60- 70	0	0	0	0	4	12	**40**	45	9	2	0	0	0	0	0	0
70- 80	0	0	0	0	0	2	6	**34**	32	8	2	0	0	0	0	0
80- 90	0	0	0	0	0	1	0	5	**20**	27	3	1	0	0	0	0
90-100	0	0	0	0	0	0	0	1	3	**17**	11	6	0	0	0	0
100-110	0	0	0	0	0	0	0	0	2	5	**3**	10	1	1	0	0
110-120	0	0	0	0	0	0	0	0	0	0	4	**8**	9	4	1	0
120-130	0	0	0	0	0	0	0	0	0	0	0	4	**12**	3	2	1
130-140	0	0	0	0	0	0	0	0	0	0	0	0	2	**5**	4	0
140-150	0	0	0	0	0	0	0	0	0	0	0	0	0	2	**3**	1
150-160	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**2**

Correct / Total data number: 648 / 1182   Accuracy: 54.8%

Figure 8. Three accuracy matrices of 12-hr intensities for 1990: (a) intensities from STIFOR vs. those from Best-Track; (b) intensities from JTWC vs. those from Best-Track, and (c) intensities from Persistence vs. those from Best-Track. Note that H0 represents 100 kt, H1 110, etc., for convenience. The interval is 10 kt. Data period is 1971-89. The boldface numbers along the diagonal represent numbers of correct forecasts.

JTWC Intensity Forecast (kt)

b

Best-Track Intensity (kt)	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-H0	H0-H1	H1-H2	H2-H3	H3-H4	H4-H5	H5-H6
0- 10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10- 20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20- 30	0	0	7	12	0	0	0	0	0	0	0	0	0	0	0	0
30- 40	0	0	9	62	24	5	0	0	0	0	0	0	0	0	0	0
40- 50	0	0	0	24	50	23	5	1	0	1	0	0	0	0	0	0
50- 60	0	0	2	5	15	21	16	7	0	1	1	0	0	0	0	0
60- 70	0	0	0	0	1	14	29	21	6	2	1	1	0	0	0	0
70- 80	0	0	0	0	1	6	21	36	17	4	0	1	0	0	0	0
80- 90	0	0	0	2	0	2	2	14	19	14	3	2	0	0	0	0
90-100	0	0	0	0	0	1	0	5	18	23	7	4	0	1	0	0
100-110	0	0	0	0	1	0	0	0	2	10	6	6	2	0	1	0
110-120	0	0	0	0	0	1	0	1	1	4	2	8	0	4	1	0
120-130	0	0	0	0	0	0	0	0	0	0	2	6	11	3	2	0
130-140	0	0	0	0	0	0	0	0	0	0	0	1	6	5	3	0
140-150	0	0	0	0	0	0	0	0	0	0	0	0	2	2	1	1
150-160	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	3

Correct / Total data number: 281 / 669 Accuracy: 42.0%

Figure 8, continued.

Persistence Intensity Forecast (kt)

Best-Track Intensity (kt)

c	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-H0	H0-H1	H1-H2	H2-H3	H3-H4	H4-H5	H5-H6
0- 10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10- 20	0	59	9	0	0	0	0	0	0	0	0	0	0	0	0	0
20- 30	0	37	233	29	5	1	0	0	0	0	0	0	0	0	0	0
30- 40	0	0	65	108	21	7	3	0	0	0	0	0	0	0	0	0
40- 50	0	0	2	46	35	22	9	4	0	0	0	0	0	0	0	0
50- 60	0	0	0	7	36	18	15	8	2	1	0	0	0	0	0	0
60- 70	0	0	0	0	3	34	17	20	5	1	0	0	0	0	0	0
70- 80	0	0	0	1	1	1	31	27	21	6	1	0	0	0	0	0
80- 90	0	0	0	0	0	1	3	17	22	18	3	2	0	0	0	0
90-100	0	0	0	0	0	0	2	9	11	25	8	3	1	0	0	0
100-110	0	0	0	0	0	0	0	4	3	3	3	7	2	1	0	0
110-120	0	0	0	0	0	0	0	0	2	6	5	8	6	2	0	0
120-130	0	0	0	0	0	0	0	0	0	0	1	4	12	5	2	0
130-140	0	0	0	0	0	0	0	0	0	0	2	4	1	2	6	0
140-150	0	0	0	0	0	0	0	0	0	0	0	1	1	4	2	2
150-160	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	2

Correct / Total data number: 573 / 1182 Accuracy: 48.5%

Figure 8, continued.

STIFOR Intensity Forecast (Kt)

a

Best -Track Intensity (kt)

	0–10	10–20	20–30	30–40	40–50	50–60	60–70	70–80	80–90	90–H0	H0–H1	H1–H2	H2–H3	H3–H4	H4–H5	H5–H6
0– 10	**0**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10– 20	0	**0**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20– 30	0	0	**1**	1	0	0	0	0	0	0	0	0	0	0	0	0
30– 40	0	0	8	**9**	8	5	3	0	0	0	0	0	0	0	0	0
40– 50	0	3	25	30	**23**	21	13	6	3	4	0	0	0	0	0	0
50– 60	0	13	53	43	35	**27**	34	34	23	15	2	6	0	0	0	0
60– 70	0	1	70	34	24	18	**20**	35	17	25	5	8	4	6	3	0
70– 80	0	0	7	4	3	2	4	**5**	7	4	7	6	2	4	2	4
80– 90	0	0	0	7	1	0	3	6	**7**	5	3	4	9	2	2	0
90–100	0	0	0	1	0	0	0	0	5	**2**	2	4	7	3	3	0
100–110	0	0	0	0	1	0	0	2	2	3	**1**	1	2	0	0	0
110–120	0	0	0	0	0	1	1	0	1	2	2	**0**	0	0	0	0
120–130	0	0	0	0	0	0	0	0	0	0	1	0	**0**	0	0	0
130–140	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0	0
140–150	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0
150–160	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**

Correct / Total data number: 95 / 875   Accuracy: 10.8%

Figure 9. Same as Fig. 8, except the accuracy matrices are for 72-hr intensities.

b

JTWC Intensity Forecast (kt)

Best-Track Intensity (kt)	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-H0	H0-H1	H1-H2	H2-H3	H3-H4	H4-H5	H5-H6
0- 10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10- 20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20- 30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
30- 40	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0
40- 50	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
50- 60	0	0	3	0	0	4	0	3	1	0	0	0	0	0	0	0
60- 70	0	0	0	0	2	0	3	7	3	2	0	0	1	1	0	1
70- 80	0	0	0	0	4	2	8	4	11	3	2	1	0	3	0	0
80- 90	0	0	0	0	2	0	0	4	9	12	1	4	2	2	2	1
90-100	0	0	0	1	1	0	0	3	3	3	0	2	1	2	3	0
100-110	0	0	0	1	0	1	0	0	5	12	7	5	1	0	0	0
110-120	0	0	0	1	0	1	2	3	1	1	1	1	0	0	0	2
120-130	0	0	0	0	0	0	0	3	4	5	4	3	8	3	3	0
130-140	0	0	0	4	1	1	1	2	0	0	0	0	7	1	2	0
140-150	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
150-160	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Correct / Total data number: 40 / 227 Accuracy: 17.6%

Figure 9, continued.

Persistence Intensity Forecast (kt)

C	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-H0	H0-H1	H1-H2	H2-H3	H3-H4	H4-H5	H5-H6
0- 10	**0**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10- 20	0	**6**	6	2	0	0	0	0	3	0	0	0	0	0	0	0
20- 30	0	37	**85**	24	1	1	3	2	6	4	0	0	0	0	0	0
30- 40	0	26	46	**12**	5	6	4	4	7	10	0	3	4	2	0	0
40- 50	0	13	26	12	**4**	4	9	7	9	5	1	0	3	1	2	0
50- 60	0	7	27	7	0	**0**	5	6	6	6	2	3	1	2	2	0
60- 70	0	3	34	14	3	1	**2**	3	3	8	1	2	1	2	1	0
70- 80	0	0	19	21	12	3	4	**9**	4	4	4	3	2	0	2	1
80- 90	0	0	4	10	7	8	9	7	**1**	1	2	5	1	4	3	3
90-100	0	0	7	11	8	15	8	1	1	**1**	1	3	2	2	0	0
100-110	0	0	4	1	2	4	2	2	1	1	**1**	2	2	1	0	0
110-120	0	0	4	5	7	2	0	2	0	3	1	**1**	3	1	0	0
120-130	0	0	3	1	2	2	3	3	2	2	3	2	**1**	0	0	0
130-140	0	0	3	2	3	0	1	1	1	1	2	0	1	**0**	0	0
140-150	0	0	0	0	1	4	1	2	0	0	0	0	2	0	**0**	0
150-160	0	0	0	2	2	0	0	0	0	0	0	0	0	0	0	**0**

Best-Track Intensity (kt)

Correct / Total data number:123 / 875 Accuracy: 14.1%

Figure 9, continued

4. Summary and Discussion

JTWC has requested that the SHIFOR (Jarvinen and Neumann, 1979) be adopted as a model for the baseline of no-skill intensity forecasting in the western North Pacific region. The adopted version is called the Statistical Typhoon Intensity Forecast (STIFOR) model which can provide twice-daily intensity forecasts up to 3 days. The results of STIFOR have been verified with post-determined best-track intensities. STIFOR forecast skill was evaluated against the skill of JTWC forecasters and a persistence method. Among the three, STIFOR has the most skill for intensity forecasts up to 24 hr. The skill of STIFOR comes from the current intensity and the last 12-hr intensity change. JTWC forecasters' skill is the best from 48 to 72 hr. The skill of JTWC comes from human judgment in a man-machine-mix environment.

The skill of STIFOR may be improved in several ways:

(1) By removing the tropical cyclone locations and their motion speeds from the parameters in Eq. (1), STIFOR can be used repeatedly for 24-hr intensity forecasts up to 72 hours.

(2) Including a periodic function in the Julian day term in Eq. (1), will allow STIFOR to better fit the Julian day parameter for seasonal variations of tropical cyclone intensity.

(3) By adding more parameters, such as sea surface temperature, divergence, vorticity and vertical motion from synoptic analysis, and nephanalysis techniques as well as forecast fields from numerical weather prediction models, STIFOR can utilize a more complete set of information. However, combining the information contents in these dynamic, kinematic and thermodynamic parameters from different sources are usually time consuming.

(4) Climatological region indices may be used instead of the exact locations of tropical cyclones in Eq. (1). For example, the correlation between the regions and the intensities could be studied by using JTWC best-track data. This kind of information grossly delineates the regional characteristics of intensity, such as terrain or low-level monsoon trough effects on intensity.

(5) The data may be stratified according to terrain zone where the terrain effects on intensity are dominant. The regional STIFOR logically provides better intensity forecasts in designated regions than the current version of western North Pacific STIFOR does. Examples of these regions are the Luzon and Mindanao Islands in Philippines, the Taiwan Central Mountain Range area, and the littoral and coastal zones of China, Japan and Korea.

(6) Using the intensity from the real-time working best-track data instead of the post-determined best-track data, STIFOR's skill can be judged realistically. This is because duty forecasters have only the working best-track data, which can be different from the post-determined best-track data.

The intensity tendency during the past 24 hr or longer has not been included in STIFOR because including such a parameter delays the issuing time of the first STIFOR forecast of a tropical cyclone. However, the information content in these data should be studied in its own right, in the realm of analog forecasting. An example in this direction is discussed in Appendix A.

It is a speculation that the intensity change has more regional variation than intensity does. If this is true, the intensity change can be designated as a predictor in a regression formula. In other words, by replacing the future intensity with future intensity change, the formulation of STIFOR can be adapted for the forecast of intensity changes. Then the future intensity becomes a sum of the current intensity and the corresponding intensity change.

There can be large fluctuations in intensity forecast skill from one tropical cyclone to another and from day to day for the same one. There is a need for an assessment of a level of difficulty of intensity forecasting in order to judge the accountability and to compare the skills of various forecast methods. The absolute error and the accuracy of 20-year intensity forecasts from the persistence method can be adapted for this purpose. An example is shown in Appendix B.

The tolerable errors of intensity forecasts are meaningful to the users despite their high variability and skewness. In a proposition paper, JTWC proposed that 5 kt should be the mean error for a 24-hr forecast of non-rapidly intensifying tropical cyclones whose central pressure tendencies are less than 24 mb in 24 hr (Elsberry *et al.*, 1992). Knowing there are so many factors which can change cyclone intensity, it seems to be a reasonable and practical recommendation that the tolerable mean errors and their variations for all tropical cyclones are 5±5, 10±5, 15±10 and 25±10 kt for the 12-, 24-, 48- and 72-hr intensity forecasts, respectively.

Choice of predictands in a regression model is significantly limited by data availability. The STIFOR model represents empirical relationships between the predictor and predictands. Better relationships can only be established with an increased knowledge of the underlying natural processes, and with an increased number of predictor types. Only then can the regression model be apodictically applied to the tropical cyclone intensity forecast. Judging the state of art of our understanding of cyclone intensity and the best-track data type, it is germane to state that the STIFOR model is far below the standard mentioned above. In addition, it is a limitation for any statistical forecast model that the results from a model can be no better than the information content of original input data. Nevertheless, STIFOR is a practical tool which provides a solution to intensity forecast problems up to two days.

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APPENDIX A

TROPICAL CYCLONE INTENSITY FORECASTS FROM THE PERSISTENCE METHOD

The persistence method assumes the intensity is constant within a forecasting period; thus, the method forecasts that the future intensity will be identical to the present one. The validity of the persistence method depends on the time scale of intensity transition of the tropical cyclone under consideration. Because of its simplicity, a forecast from the persistence method is also called a "blind" or "no-skill" forecast. A forecast from the persistence method can be used as a baseline for an operational forecast; in other words, the forecast skill score of a another method can be measured as the difference between the forecasts obtained by using that method and the persistence method.

The 46-year (1945-91) post-determined best-track intensity data for the western North Pacific were used to demonstrate the validity of the persistence method. The data consist of current intensity, the past 48- and 24-hr intensities, and the future 24-, 48- and 72-hr intensities. Table A1 lists the statistics of these data in terms of mean, standard deviation, skewness, and kurtosis. The statistics reveal that the data have nearly normal distributions which are rather flat and positively skewed. The cross-relations between the current intensity and the past and the future intensities are summarized in Tables A2 and A3. In Table A2, the pair of intensities which differ by a 24-hr span have lower root-mean-square difference, but higher correlation, covariance and accuracy, than those which differ by either 48- or 72-hr spans. In Table A3, the correlations between the intensities with 24 and 48 hours separation are much higher than those with 72 and 96 hours separation. This implies that there is useful information between two intensities when they are separated by 36 to 48 hours or less. As an example, statistically speaking, the past 24-hr intensity can help the 12- to 24-hr intensity forecast.

Table A1. Forty-six-year (1945-91) statistics of past 48-hr, past 24-hr, current, 24-, 48-, and 72-hr tropical cyclone intensities for the western North Pacific, namely, I_{-48}, I_{-24}, I_0, I_{24}, I_{48}, and T_{72} . The statistics contain number of data (Data #), mean, standard deviation (SD), skewness, and kurtosis.

	Data #	Mean(kt)	SD	Skewness	Kurtosis
I_{-48}	12274	61.33	32.53	0.73	-0.12
I_{-24}	14738	60.41	31.27	0.77	0.06
I_0	17251	57.33	30.50	0.91	0.36
I_{24}	14738	61.01	30.73	0.80	0.14
I_{48}	12275	63.74	31.39	0.72	-0.05
I_{72}	9958	65.16	31.95	0.64	-0.15

Table A2. Forty-six-year (1945-91) statistics of relationships between the current intensity I_0 and the past 48-, past 24-, future 24-, 48- and 72-hr intensities. The time differences between intensities are shown in the first row. The statistics consist of four parts: root-mean-square difference (RMS, in kt), coefficient of linear correlation (COR), covariance (COV, in 10^2 kt^2), and accuracy in percentage for a 10-kt interval (ACCU).

	$< I_0 , I_{-48} >$ 48 hr	$< I_0 , I_{-24} >$ 24 hr	$< I_0 , I_{-24} >$ 24 hr	$< I_0 , I_{-48} >$ 48 hr	$< I_0 , I_{-72} >$ 72 hr
1. RMS	33	21	21	33	40
2. COR	0.479	0.775	0.776	0.480	0.244
3. COV	5	9	8	5	3
4. ACCU	13	22	22	13	10

Table A3. Forty-six-year (1945-91) statistics of relationships between the past 24-hour intensity I_{-24} and the current, the future 24-, 48- and 72-hr intensities. The time difference between intensities are shown in the first row. The statistics consist of four parts: root-mean-square difference (RMS, in kt), coefficient of linear correlation (COR), covariance (COV, in 10^2 kt^2), and accuracy in percentage for a 10-kt interval (ACCU).

	$< I_{-24} , I_0 >$ 24 hr	$< I_{-24} , I_{24} >$ 48 hr	$< I_{-24} , I_{48} >$ 72 hr	$< I_{-24} , I_{72} >$ 96 hr
1. RMS	21	33	40	45
2. COR	0.775	0.480	0.242	0.072
3. COV	9	5	3	1
4. ACCU	22	13	10	9

APPENDIX B

A COMPARISON BETWEEN 20-YEAR AND 1-YEAR INTENSITY FORECASTS FROM THE PERSISTENCE METHOD

Twenty-year (1971-90) and one-year (1990) intensity forecasts from the persistence method are verified with the post-determined intensity from JTWC best-track data. Table B1 is a statistical comparison. The results for the two periods have similar root-mean-square and absolute errors. The correlation of the 20-year intensity forecast decreases faster than that of the one-year forecast for the 12- to 72-hr forecast period. The covariance indicates that the intensities during the two periods have similar magnitudes. In terms of accuracy, results of 1990 are about 14-27% better than these of the 20 years. It is hoped that this number can be used to measure the degree of difficulty of tropical intensity forecasting.

Table B1. Verifications of 1971-90 results from persistence with the post-determined best-track intensity for the western North Pacific. The statistics consist of five parts: root-mean-square error (RMSE, in kt), mean and standard deviation of absolute error (AE, in kt), coefficient of linear correlation (COR), covariance (COV, in 10^2 kt^2), and accuracy in percentage for a 10-kt interval (ACCU). The numbers of available data are in the parentheses of RMSE Part. The values in the parentheses of AE Part are the standard deviations.

	Data period	12-hr	24-hr	48-hr	72-hr
1. RMSE	1971-90	11(14344)	18(13285)	30(11198)	38(9217)
	1990	9 (1182)	17 (1120)	30 (996)	39 (875)
2. AE	1971-90	10 (7)	16 (12)	25 (18)	32 (23)
	1990	10 (6)	16 (11)	25 (19)	33 (24)
3. COR	1971-90	0.93	0.80	0.50	0.24
	1990	0.96	0.86	0.59	0.34
4. COV	1971-90	8	7	5	2
	1990	10	9	6	4
5. ACCU	1971-90	43	25	15	11
	1990	49	30	17	14